

Hadronic Showers from Extremely-high-energy ν_e Interactions

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There is an increasing interest in searching for extremely-high-energy astrophysical ν_e . Several groups have recently reported limits on the ν_e flux at energies above 10^{20} eV, based on searches for coherent radio or acoustic radiation from neutrino-induced showers[1]. These limits rely on an accurate understanding of the shower development since the frequency spectrum of the radiation depends on the length and width of the shower.

At very high energies, the Landau-Pomeranchuk-Migdal effect reduces the cross sections for electron bremsstrahlung and e^+e^- pair production. At the same time, the photonuclear and electronuclear cross sections rise slowly with energy. As Figure 1 shows, in solids and liquids, above 10^{20} eV, the photonuclear cross section is larger than the pair production cross section, and electrons and photons interact hadronically, producing a hadronic shower. Even at lower (IceCube) energies, the hadronic cross sections are large enough that electromagnetic showers can develop hadronic components, leading to phenomena like increased muon production.

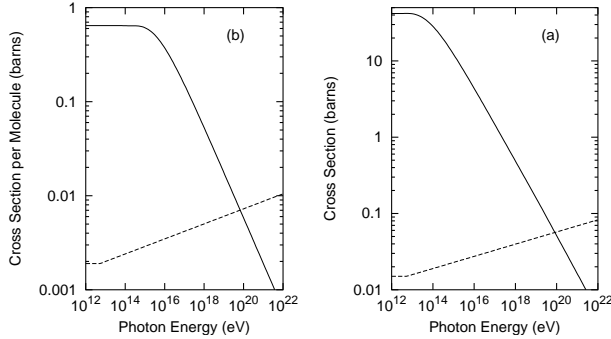


FIG. 1: Comparison between the pair production (solid lines) and photonuclear (dashed lines) cross sections in (a) water and (b) lead.

This hadronic character changes the length and width of ν_e induced showers [2]. Figure 2 compares the lengths of ν_e showers with and without photon-hadron interactions. At ν_e energies below 10^{17} eV, the shower length rises logarithmically with the energy E . Above 10^{17} eV, the LPM effect reduces the cross sections, and the shower length rises as $E^{1/3}$. Above 10^{20} eV, hadronic interactions become dominant, and, by increasing the cross sections, shorten the shower. In Fig. 2, the brown dotted line shows the shower length with hadronic interactions, while the solid blue line neglects photonuclear interactions. With photonuclear interactions, the showers are significantly shorter.

In addition to shortening the showers, the presence of

hadronic interactions is likely to widen them. Particles produced in hadronic interactions have a transverse momentum (p_T) scale of order $\Lambda_{QCD} \approx 300$ MeV/c, while for electromagnetic interactions, $p_T \approx 0.5$ MeV/c.

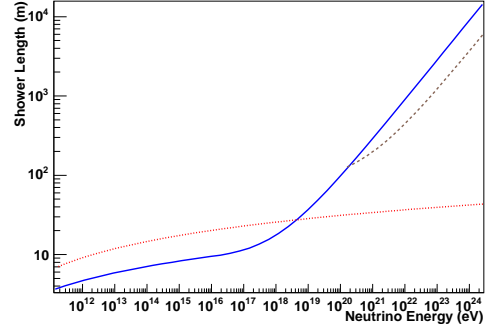


FIG. 2: Shower length as a function of ν_e energy. The solid blue line is for purely electromagnetic showers, while the dashed brown line is for showers that allow for photonuclear interactions. The dotted red line is for purely hadronic showers.

Most of the radiation from a shower is emitted coherently. Coherence occurs when the wavelength of the radiation is larger than the size of the shower along the direction of the radiation (the Cherenkov angle for electromagnetic radiation, and transverse to the shower for acoustic radiation). Any width increase reduces the higher-frequency radiation from a shower. Length reductions also affect the radiation, albeit in a less straightforward manner.

The effects of hadronic interactions are not included in recent calculations of radiation from ν_e induced showers. Consideration of photonuclear interactions may affect several published limits on the flux of astrophysical ν_e at energies above 10^{20} eV. At lower ν_e energies, down to 10^{16} eV, as are studied by optical detectors like IceCube, photonuclear interactions will lead to increased muon production, along with smaller changes in shower shape.

REFERENCES

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